Fast Radiative Shocks in Dense Media. III. Properties of the Emission

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ABSTRACT

Evolution of fast, radiative shocks in high density medium is presented. Ionizing spectra and approximate broad band light curves of the shocked gas are calculated. Emergent shock spectra, as seen by a distant observer, are obtained from photoionization models. The emergent spectra have a power-law shape $F_\nu \propto \nu^{-\alpha}$ with mean spectral index $\alpha \sim 0.6 - 1.0$ in the energy range $0.01 - 10$ keV, and have a high-energy cut-off corresponding to the original shock velocity. It is shown that the models exhibit promising features that may account for some photometric and spectral properties of Active Galactic Nuclei.

Key words: hydrodynamics – shock waves – instabilities – ISM: supernova remnants – galaxies: active – X-rays: galaxies

1 INTRODUCTION

In the series of papers Terlevich and his group (see, e.g., Terlevich et al. 1992) developed the starburst model for Active Galactic Nuclei (AGNs). In this model AGN is powered by compact, dense supernova remnants (cSNRs), and the bulk of radiation is emitted by the supernova shock wave evolving in a dense medium ($n_0 \sim 10^7$ cm^{-3}). Terlevich et al. (1992) calculated 1D and 2D hydrodynamical models of cSNR evolution and demonstrated that it was possible to recover observed characteristics of Broad Line Region of AGNs. Using very simple assumptions Terlevich et al. (1994a, TTRFM) successfully explained observed difference between moments of maximum continuum and line emission taking into account dependence on ionization parameter. While the rapid X-ray variability of AGNs still remains to be explained in this model, preliminary investigations (Terlevich et al. 1994b) showed that interactions between dense, fast moving clumps of gas could be partially responsible for observed variations of high-energy emission. Detailed criticism of the starburst model was presented by Heckman (1991) and Filippenko (1992).

Apart from their hypothetical presence in AGNs, compact supernova remnants were detected in nearby galaxies. On the basis of spectroscopic studies such objects like SN 1980K (Fesen & Becker 1990), SN 1987F (Filippenko 1989), or SN 1988Z (Stathakis & Sadler 1991; Turatto et al. 1993) are interpreted as supernova remnants evolving in a medium of density as high as 10^7 cm^{-3}. The lack of appropriate theoretical models was noted by Leibundgut et al. (1991) in

their study of SN 1986J and SN 1980K. Both the possible role of cSNRs in AGNs and the remark by Leibundgut et al. gave motivation to our work on hydrodynamical evolution of fast shocks evolving in a dense environment.

The subject is not new. Over a decade ago Chevalier & Imamura (1982) showed that radiative, steady shocks are subject to an oscillatory instability. This result was confirmed on the basis of nonlinear hydrodynamical analysis for nonstationary shocks (Gaetz, Edgar & Chevalier 1988; Stone & Norman 1993) as well as for steady radiative shocks (Innes, Giddings & Falle 1987). Both groups found unstable behavior of shocks faster than ~130 km s^{-1}. The spectra of faster shocks ($v_s \leq 1100$ km s^{-1}) were discussed in some detail by Binette, Dopita & Tuohy (1985). They found that the emergent shock spectrum can be approximated by a power-law with a spectral index $\alpha \sim 0.5$ for energies lower than ~ 1 keV. However, all theoretical investigations mentioned above apply to relatively slow shocks in low density medium ($n < 100$ cm^{-3}). Therefore, they are not applicable to conditions expected for cSNRs or for central regions of AGNs.

In the first paper of the series (Plewa & Różyczka 1992, Paper I) we investigated the evolution of fast ($v_{s0} \geq 1000$ km s^{-1}) radiative shocks in a uniform medium of density $n = 10^7$ cm^{-3}. The shock and its post-shock region were found to be highly nonstationary, leading to the conclusion that some stochastic component might be present in the evolutionary pattern, but we failed to obtain any definite results due to the low resolution of the models. Subsequently, we used a high-resolution adaptive grid technique (Plewa 1993, Paper II) and we found quasiperiodic patterns in the evolution of the shocks. The flow behind the main shock was found to be highly discontinuous due to the presence

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of secondary shocks leading to a stochastic behavior of the shock luminosity.

In Paper I and II our model shocks were formed by the reflection of a steady stream of gas from a rigid wall, and they were not directly applicable to any astrophysical situation. In the present paper we improve the models by allowing for a secular decrease in stream velocity to mimic the evolution of the forward SN shock. Also, approximate spectra of shocks are obtained under the assumption of collisional equilibrium. Description of the method is given in Section 2. In Section 3 and 4 we present details of the shock evolution, the broad band photometry and the spectrum of the radiation emitted by the shock, as well as results obtained from photoionization models. Possible relation of the models to AGNs is discussed in Section 5.

2   THE METHOD

The hydrodynamical evolution of the shock is modeled using *Piecewise Parabolic Method* (PPM) of Colella & Woodward (1984) in 1D plane-parallel geometry. Our preliminary investigations presented in Paper I showed that even the high resolution of the PPM scheme is not sufficient to model accurately the most luminous and dense regions of the shocked gas if a standard uniform grid is used. The evolution of such regions is characterized by cooling time scale much shorter than the dynamical scale of the flow. For example, to avoid complications arising from the lack of resolution in strongly radiating regions Blondin, Fryxell & Königl (1990) used a *special treatment* lowering artificially local emission rates. Our numerical experiments showed that such procedure strongly affects the results, and we concluded that to model the evolution correctly a much higher resolution should be used.

We found that to resolve thin, strongly radiating regions of shocks faster than ~ 1000 km s^{-1} the grid should contain about 10^4 equally spaced zones. The cheapest way to obtain such a high resolution is the adaptive grid method. In our approach presented in Paper II the grid motion is governed by an adaptive grid algorithm developed by Dorfi & Drury (1987). The grid points are distributed accordingly to a user-defined *resolution function*. For our problem the resolution function was defined as the sum of gradients of density, internal energy, and emission rate (see Paper II for details). We also added the term proportional to the gas density to obtain higher resolution in high density regions. The grid equation was solved implicitly at the beginning of every hydrodynamical time step. The grid was divided into 500 zones and we used Courant number equal to 0.8. The number of time steps needed to complete the evolution using maximum point concentration equal to 2.2×10^4 was about 2×10^5.

At the left boundary of the grid we impose a reflecting boundary condition, while from the right side the grid is fed with gas of constant density and temperature. To mimic the decrease of shock velocity in a way appropriate for SN shock we vary the velocity of the inflowing gas with time as

$$v_{\rm in} = v_0 \times (t/t_{\rm sg} + 1)^{-\frac{5}{7}},$$

where $t_{\rm sg}$ has the interpretation of the time that has to elapse

Figure 1. Schematic representation of initial conditions for shock evolution.

since the SN explosion before cooling effects become noticeable. According to Shull (1980)

$$t_{\rm sg} = 0.63 E_{\rm SN} \left(\frac{n_0}{10^7} \right)^{-3/4} \;\; {\rm yr},$$

if the explosion energy is $E_{\rm SN} \times 10^{51}$ erg and the density of the ambient medium is n_0. This way we account for the fact that in $\sim t_{\rm sg}$ years after the SN explosion the mean velocity of the forward SN shock begins to decline like $(t/t_{\rm sg})^{-5/7}$ (Shull 1980; see also Fig. 3 in Falle 1981).

This set of initial and boundary conditions leads to the formation of a strong shock at the left boundary of the grid (Fig. 1). The initial velocity of the shock for constant gamma-law gas with $\gamma = 5/3$ is given by $v_{\rm s0} = \frac{4}{3} v_0$. Let us note that, when compared to real SNR, the left boundary of the grid can be regarded as the interface between the ejecta and the gas shocked by the forward supernova shock. Thus, the advantage of our approach is the possibility to concentrate all grid points in the most interesting narrow region of the remnant where strong cooling occurs. The disadvantage is the simplified boundary condition imposed at the left edge of the grid, which in general may influence the structure and dynamics of the dense shell. This, however, does not happen in the case of shock with $v_{\rm s0} \geq 3000$ km s^{-1} which form their shells far away from the left edge of the grid (Fig. 3). The reflecting boundary condition affects only the models of shocks with $v_{\rm s0} < 3000$ km s^{-1}, which form two shells, one of them being attached to the left edge of the grid (Fig. 3a). However, as the latter shell is much less massive than the shell formed close to the main shock, the influence of the boundary condition on both the dynamics and luminosity of the post-shock region as a whole is marginal.

Following Terlevich et al. (1992) and TTRFM, we assume for the ambient medium a density $n_0 = 10^7$ cm^{-3} and a temperature $T_0 = 10^4$ K. These values are admittedly arbitrary. However, the choice of temperature is practically unrestricted because of high shock velocities (the shock would remain very strong even if T_0 was an order of magnitude higher). As for the density, it was shown in Papers I and II that its reduction or increase results respectively only in increase or reduction of the evolutionary time scale and the size of the post-shock region, while all characteristic

evolutionary features of the model remain unchanged. The adopted value of $n_0 = 10^7$ is particularly interesting because of indications that it may be characteristic of the medium surrounding cSNRs.

Radiative losses are allowed for in the post-shock region, while the shock moves to the right through the yet unshocked gas. The losses are calculated implicitly assuming collisional equilibrium conditions for optically thin plasma with solar abundances. We use cooling function obtained with the help of CLOUDY 84.06 code (Ferland 1993). We assume that the heating/cooling balance is achieved at a temperature equal to the temperature of the unshocked ambient medium $T_{min} = T_0 = 10^4$ K. Therefore, in the regions where temperature has dropped below T_{min} (e.g. due to gas expansion) the temperature was increased to reach the lower limit given above.

Also under the assumption of collisional equilibrium, spectra of the radiation emitted by the hot shocked gas are calculated at selected evolutionary moments. These spectra will be called *ionizing spectra* in order to distinguish them from the *emergent shock spectra* obtained from photoionization calculations presented in Section 4.2 below (the latter are the spectra emerging from our models which would be registered by a distant observer if the space between the observer and the shock would be empty.) To save the CPU time, in place of the extremely time consuming CLOUDY code we use the following approximations for calculation of the ionizing spectrum. Continuum emission consists of the f-f emission with approximate Gaunt factor calculated after Hummer (1988), while the b-f and 2-photon emissions are calculated using formulae given by Mewe, Lemen & van den Oord (1986). Contribution from over 2600 lines is calculated using line emissivities taken after Stern, Wang & Bowyer (1978) and Mewe (1992) (see also Mewe, Gronenschild & van den Oord 1985).

In order to estimate the relative broad band distribution of energy in the ionizing spectrum we define a set of three filters corresponding to wavelength intervals $\lambda \leq 100$ Å (high energy, HE), $100 < \lambda \leq 905$ Å (medium energy, ME), and above 905 Å (low energy, LE). The filter transmission function is defined as a fraction of the total energy emitted at a given temperature per given wavelength interval (LE, ME, HE; Fig. 2). The transmission functions are calculated by detailed integration of the spectrum emitted by the optically thin plasma as given by the CLOUDY code.

Crucial to our approach is the assumption of collisional equilibrium which makes the problem numerically tractable. Admittedly this assumption does not work well in the lower temperature range. However, it is justified for the bulk of the shocked gas with temperatures higher than 5×10^5 K (only below that value the cooling function begins to be history dependent; see, e.g., Shapiro & Moore 1976; Gaetz et al. 1988). Moreover, as it was demonstrated by Gaetz et al. (1988) details of cooling are not very important for global shock dynamics (obviously, they play a more significant role in the evolution of cold regions with $T < 10^5$ K). The cool regions are the source of ultraviolet and optical radiation only and we do not expect significant changes of the high energy emission when nonequilibrium effects would be considered. These issues are further discussed in Sect. 4.2. We do not calculate preionization structure of the gas upstream from the shock. Also, we give here only results for solar composi-

Figure 2. Definition of the broad band filters. HE, ME, and LE filter transmissions are drawn by thick, thin and dotted lines, respectively.

tion, although higher metallicity would be more appropriate for both cSNR and AGN applications. Taking all the simplifications into account, our shock spectra are to be treated as first approximation only, especially in LE and ME ranges. On the other hand, we are fairly confident that the dynamics of the shocks has been modeled properly, and that any improvements in the treatment of cooling processes would not affect dynamical evolution of the shocks in a significant way.

3 DYNAMICAL EVOLUTION

We calculated models for initial shock velocities equal to 1000, 2000, 4000, and 6000 km s^{-1}. It should be stressed here that only the fastest shock model may be directly related to cSNRs evolving in a uniform medium of $n_0 = 10^7$ cm^{-3}, as, according to Shull (1980), in such a case the velocity of the SN shock at $t = t_{sg}$ is equal to ~ 6000 km s^{-1}. The remaining models have no direct application, and they only serve to illustrate the strong dependency of the evolution on v_{s0} (one may expect, however, slower SN shocks to appear in nonuniform media, e.g., in dense shells of wind bubbles blown by progenitors.)

Here we present details of the evolution for shocks of velocities equal to 2000 (the *slow* shock) and 6000 km s^{-1} (the *fast* shock), as the evolution in the two remaining cases shows no qualitatively new features. The evolution was followed up to evolutionary time $t = 3$ yr and $t = 12$ yr for slow and fast shock, respectively. Summary of the results for all the cases considered is presented in Table 1. Note that the total shock luminosity was calculated assuming that the radius of the emitting sphere is equal to $R_{sh} = 3 \times 10^{16}$ cm (see Fig. 8a of Terlevich et al. 1992). Evolution of the model shocks in form of a sequence of vertically shifted density plots in logarithmic scale is shown in Fig. 3 (all plots were taken at equidistant intervals of time). The left boundary of the plot corresponds to the contact discontinuity between the ejecta and the ambient medium, and the ambient gas enters the grid from the right side.

Figure 3. Density evolution of model shocks. (a) initial shock velocity: $v_{s0} = 2000$ km s^{-1}; distance scale: 1.1×10^{15} cm; time scale: 3 years; density scale: $1.78 \times 10^{-18} - 2.90 \times 10^{-13}$ g cm^{-3}; (b) initial shock velocity: $v_{s0} = 6000$ km s^{-1}; distance scale: 1.2×10^{16} cm; time scale: 12 years; density scale: $1.79 \times 10^{-18} - 1.26 \times 10^{-13}$ g cm^{-3}. The vertical scale may be read from the jump in the lowermost which corresponds to an increase of density by a factor of 4. See text for details.

Table 1. Basic parameters of the model shocks.

v_{s0} km s^{-1}	R_{max} cm	F_{max} erg cm^{-2}s^{-1}	L_{max} erg s^{-1}
1000	1.8×10^{14}	7.5×10^{6}	9.4×10^{40}
2000	1.0×10^{15}	3.7×10^{7}	4.7×10^{41}
4000	4.7×10^{15}	8.7×10^{7}	1.1×10^{42}
6000	1.2×10^{16}	1.5×10^{8}	1.9×10^{42}

v_{s0} – the initial shock velocity; R_{max} – the maximum extension of the shock; F_{max} – the maximum energy flux; L_{max} – total shock luminosity assuming the radius of the emitting sphere equal to $R_{sh} = 3 \times 10^{16}$ cm.

3.1 Evolutionary phases

In all cases listed in Table 1 the evolution of the shock could be divided into three distinctive phases:

(1) *Nearly adiabatic shock expansion.* The evolution starts with a nearly adiabatic shock expansion as cooling is ineffective at temperatures over 10^7 K for typical cooling function (see Raymond, Cox & Smith 1976). As both temperature of radiating gas and velocity of inflowing gas decrease with time, the shock slows down while cooling efficiency begins to grow with temperatures falling below 10^7 K.

(2) *Thin shell formation.* At temperatures lower than $\sim 10^6$ K the cooling time scale suddenly drops down. This phenomenon is known as *catastrophic cooling* (Falle 1975, 1981) and it results in formation of thin transition regions (hereafter referred to as *cooling waves*) in which thermal energy of the gas is rapidly radiated away at nearly constant density. The cooling waves are the source of almost all the emission generated by the model in ME and LE energy bands. As

our resolution function contains the term proportional to the luminosity gradient, cooling waves are well resolved.

Soon after the formation of cooling waves the cool gas begins to condensate into a very thin and dense shell, visible as the highest peak in both panels of Fig. 3 (the less prominent spikes in Fig. 3 originate from minor flow discontinuities like weak shocks). At this moment the grid points strongly concentrate in the region of shell formation (the maximum grid concentration corresponds to 2.2×10^4 equally spaced zones). This grid concentration is close to a practical upper limit, as at significantly higher resolutions the time step becomes prohibitively short due to the CFL condition. This phase of the evolution really challenges our adaptive grid method which has to redistribute the grid points between the main shock profile, the fast moving cooling waves, and the rapidly growing shell. All these structures are well resolved, proving the efficiency of the method.

(3) *Oscillatory instability of the main shock.* Finally, loss of the pressure in the post-shock region due to cooling leads to the recession of the main shock, and to its reflection from the dense shell marked by a kink in shock position in Fig. 4, in which position and velocity of the shocks are plotted against time. In Paper I we showed that the velocity of the reflected shock depends on momentary structure of the shell and parameters of the inflowing gas. At the moment of the shock reflection the velocity of the inflowing gas is by a factor of few lower than at the beginning of the evolution. This implies lower velocities of the reflected shocks ($v_{rs} < 1000$ km s^{-1}) and, therefore, shorter evolutionary time scales. The evolutionary time scale of the main shock is additionally reduced due to strong cooling in the region just behind the shock, as after the reflection the temperature of the post-shock gas never exceeds 10^7 K. The mean period of the oscillations is roughly equal to $P_{osc} \approx 14.5$ d and $P_{osc} \approx$

Figure 4. Temporal variations of position and velocity of the main shock (dashed and solid lines, respectively). (a) initial shock velocity $v_{s0} = 2000$ km s^{-1}; distance scale: 1.04×10^{15} cm; velocity scale: 2000 km s^{-1}. (b) initial shock velocity $v_{s0} = 6000$ km s^{-1}; distance scale: 1.18×10^{16} cm; velocity scale: 6000 km s^{-1}.

3.3 d for fast and slow shock, respectively. The period of the main shock oscillations corresponds to the fundamental mode of the oscillatory instability discussed by Chevalier & Imamura (1982) and Gaetz et al. (1988). The oscillatory phase is preceded by a relatively short period of time during which the density contrast between the inflowing gas and the shell is too low for the shock reflection to occur (the reflected shock is very weak and its cooling time is extremely short). This phase is marked by a chaotic behavior of luminosity and velocity of the main shock. Semi-regular oscillations begin only after the density contrast has become high enough for an efficient shock reflection.

3.2 Dependence of the evolution on shock velocity

In both cases described above the evolution starts with a nearly adiabatic expansion of the main shock followed by formation of the thin shell. In the case of the fast shock ($v_{s0} = 6000$ km s^{-1}, Figs. 3(b), 4(b), and 5b) the shell condenses far away from the rigid left boundary of the grid, and it moves outwards due to high pressure in the hot, rarefied gas left behind it. This region (called *hot cavity* by Terlevich et al. 1992) is created as the post-shock temperature drops faster due to rapidly decreasing inflow velocity than due to cooling (as a result, catastrophic cooling occurs closer to the shock). This is not true for shocks slower than ~ 3000 km s^{-1} as the initial post-shock temperatures are lower by an order of magnitude and, therefore, the cooling is much more effective. In that case the shell recedes to the left, and we observe the formation of the second shell at the left boundary of the grid. The collision of two shells at the end of the run for slower shock (upper left part of Fig. 3a) is marked by prominent luminosity spike at time $t \approx 2.5$ yr (Fig. 5a). Finally even for shocks of higher velocities the shell will collide with the left boundary of the grid.

4 PHOTOMETRIC AND SPECTRAL FEATURES

4.1 Broad band emission

The behavior of the broad band emission of ionizing radiation produced in the post-shock region is shown in Fig. 5. During the first evolutionary phase associated with nearly adiabatic shock expansion the total luminosity smoothly increases, and the shock slows down. At the moment of shell formation LE/ME luminosities rapidly increase while HE emission remains nearly constant. Fast variability of LE/ME emission during shell formation indicates nonuniformity of the gas entering the shell. This nonuniformity of the cool, condensing gas arises from small, numerical fluctuations present in the post-shock region of nearly standing main shock (see Fig. 3) which are amplified by catastrophic cooling.

After shell formation (at $t \approx 1$ and $t \approx 3.2$ yr for slow and fast shock, respectively) the HE luminosity steadily declines. The decline rate is higher for the slow shock, as in this case the hot region behind the shell has lower temperature. In the case of fast shock this hot, rarefied gas radiates the rest of its thermal energy at $t \approx 10.5$ yr.

The main shock reflection from the shell ($t \approx 1.6$ yr, Figs. 4(a) and 5(a); $t \approx 5.0$ yr, Figs. 4(b) and 5b) is marked by the kink in shock position and an intense burst of the LE/ME radiation. From now on, LE and ME luminosities begin to oscillate on a time scale roughly corresponding to the fundamental mode of the oscillatory instability (Sect. 3.1). Note that the post-shock region of the oscillating shock does not radiate in HE, therefore, no rapid variations of the high energy emission are expected.

For reasons explained in Sect. 3.1 in the next two sections we will concentrate our discussion on the spectrum emitted by the shock of original velocity $v_{s0} = 6000$ km s^{-1} (roughly equal to the velocity of the forward shock considered by Terlevich et al. 1992).

4.2 The continuum

The emergent shock spectrum just after the thin shell formation (at $t \approx 3.20$ yr, i.e. at the moment the shock achieves its maximum luminosity) is shown in Fig. 6. The energy flux

Figure 5. Temporal variations of total, HE, ME, and LE luminosity of the post-shock region (thick, medium, thin and dotted lines, respectively). (a) initial shock velocity $v_{s0} = 2000$ km s^{-1}; luminosity scale: 3.71×10^7 erg cm^{-2}s^{-1}. (b) initial shock velocity $v_{s0} = 6000$ km s^{-1}; luminosity scale: 1.52×10^8 erg cm^{-2}s^{-1}.

Figure 6. The emergent spectrum of the shock 6000 km s^{-1} at time $t = 3.20$ yr, just after the thin shell formation. (a) emergent flux; (b) transmitted flux; (c) solid line: sum of the reflected flux and half of the flux generated between the main shock and the shell; dashed: reflected flux only. The energy flux νF_ν (erg cm^{-2}s^{-1}) is plotted in logarithmic scale. Bottom and top scales are given in logarithm of energy in Rydbergs and keV, respectively. See text for details.

νF_ν (Fig. 6a) is the sum of three components (Figs. 6(b) and 6c):

(1) the transmitted flux (originating between the shell and the left edge of the grid, and partly absorbed by the shell);
(2) the half of the flux generated between the main shock and the shell (emitted directly towards the observer);
(3) the reflected part of the second half of flux generated between the main shock and the shell (originally emitted towards the shell and reflected by the shell towards the observer).

The emergent spectrum has a power-law shape $F_\nu \propto \nu^{-\alpha}$ with a mean spectral index $\alpha \approx 0.63$, and with a high-energy cutoff around 10 keV. For energies above few keV the spectrum is completely dominated by the emission produced by the hot region between the shell and the left boundary of the grid that has not yet had enough time to cool down due to its very high initial temperature (see Sections 3.2 and 4.1). This part of the spectrum is unlikely to be affected by any improvement of cooling function for nonequilibrium effects. For lower energies, most of the radiation comes from the post-main-shock region located between the main shock and the shell. The UV/optical emission is produced by the shell ionized predominantly by photons emitted from the hot region obscured by the shell. As the emission from this region is modeled correctly, the low-energy part of the shock spectrum is also calculated correctly.

4.3   The line emission

The ionizing flux, as defined in Sect. 2, consists of two components only:

(1) the flux originating between the shell and the left edge of the grid;
(2) half of the flux generated between the main shock and the shell.

Table 2. Time lags for selected emission lines.

line	time lag [d]		
	observed	TTRFM	this paper
Hβ λ4861	20	30-40	17.9
Lyα λ1216	12	1-15	5.1
He II λ1640	4-10	12-20	5.1
Mg II λ2798	34-72	40-50	40.5
C III] λ1909	26-32	20-30	25.2
Si IV λ1397	12-34	12-17	5.8
C IV λ1549	8-16	10-15	3.3
N V λ1240	4	2-10	5.1

The ionized medium was identified with the dense shell. The shell of the 6000 km s^{-1} shock contained $\sim$ 50 zones and its average thickness was $\sim 4 \times 10^{13}$ cm. At selected evolutionary times the ionizing spectra together with corresponding shell models were used as the input to CLOUDY photoionization code.

The output from CLOUDY consisted of intensities and intensity ratios of selected lines as functions of time. It was found that due to finite time of the shell formation line intensity maxima lagged behind ionizing flux maximum, the lag being shorter for high ionization lines, and longer for low ionization ones (Table 2). Temporal variations of selected line intensities and ionizing flux intensities during the shell formation phase are shown in Fig. 7. Fig. 8 presents temporal variations of selected line ratios throughout the simulated evolution together with variations of the total hydrogen column density N(H) and maximum density of the shell n_{max}.

5   DISCUSSION

The general conclusion of our calculations is that the basic features of the fast shock model are similar to those observed in AGNs.

First, the emergent spectrum of the shock has a power-law shape $F_\nu \propto \nu^{-\alpha}$ with a mean spectral index of $\alpha \approx 0.63$, and with a high-energy cutoff around 10 keV. Note that the hard X-ray $(2 - 10 \text{ keV})$ AGN spectrum is characterized by a single power-law with $\alpha = 0.7$ (Turner & Pounds 1989). The high energy end of the spectrum (hereafter the cutoff energy) is produced by the gas located behind the shell, and we recall that this gas was processed at the beginning of evolution by the shock moving with a velocity nearly equal to the original shock velocity. Assuming that the cooling was ineffective and the temperature of the gas did not change appreciably till the time of the shell formation we can state that the cutoff energy is directly related to the original shock velocity. Therefore, one may expect that the spectrum of the shock with the initial velocity equal to the initial velocity of a supernova blast wave $(v_{\mathrm{s0}} = 1 - 2 \times 10^4 \text{ km s}^{-1})$ would have the energy cutoff at around 100 keV, as the post-shock temperature is proportional to square of the shock velocity (such models were not obtained as we considered evolution for $t \geq t_{\mathrm{sg}}$, see Sect. 3). This is the cutoff value expected for Seyfert galaxies (see Zdziarski, Życki & Krolik (1993b) for references). Note also that our model shock spectrum very closely resembles thermal Comptonization component

used in calculations of X-ray spectra of AGNs (Zdziarski et al. 1993b, Zdziarski, Lightman & Maciołek-Niedźwiecki 1993a).

Second, intensity ratios of spectral lines produced in the photoionized shell agree fairly well with those measured in AGNs (Fig. 8). The values for AGNs in Fig. 8 were taken after compilation of Kwan & Krolik (1981), and they are marked on the vertical axes by dots. We also confirm preliminary results obtained by Terlevich et al. (1992). The predicted total hydrogen column densities of the ionized medium are of the order of 10^{23} cm^{-2} and the maximum gas density is roughly equal to 10^{11} cm^{-3}. Our model fails in explanation of low Lyα/Hβ ratio, but this problem is common for other photoionization models of AGNs.

Finally, our model exhibits *time lag*, i.e. a delay between maxima of ionizing continuum intensity and line intensities. TTRFM using a very simple model of the shell and ionizing continuum obtained time lags listed in Table 2. With our study, which is entirely free of arbitrary assumptions concerning the shell and the ionizing continuum, we corroborate their findings. The predicted time lags agree well with those observed in AGNs. However, this result should be treated with some caution as the observational definition of the time lag (involving statistical measurements) is different from the one employed here.

Taken together, the above properties provide an indication that cSNRs play a significant role in the AGN phenomenon, as it was proposed in the starburst model (see, e.g., Terlevich et al. 1992). One may be almost sure that more sophisticated model spectra based on appropriate assemblage of shocks with different velocities would recover the ME excess observed in AGNs (i.e. the so called big blue bump, Turner & Pounds 1989). This is because in a massive starburst there will be many cSNRs coexisting, most of them in relatively long lasting advanced evolutionary phases characterized by low shock velocities. Such models would also enable statistical measurements of time lags better suited for comparison with observations than these presented here.

Our conclusion is that cSNR shocks are an attractive research field whose exploration has only begun here. The finding that time lag phenomena may be related to variations of physical parameters of the photoionized medium (as originally proposed by TTRFM) seems to be particularly attractive and it clearly deserves future investigation.

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Figure 7. Temporal variations of selected line intensities and ionizing flux during formation of the shell for initial shock velocity $v_{s0} = 6000$ km s^{-1}. All values are shown in logarithmic scale; time is given in years on horizontal axis. Vertical line marks the time of maximum intensity of ionizing flux.

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Figure 8. Temporal variations of selected line ratios and parameters derived from photoionization models for initial shock velocity $v_{s0} = 6000$ km s^{-1}. Left scale: full line; right scale: dotted line. Line ratios typical for AGNs are marked by dots on vertical axes. All values are shown in logarithmic scale; time is given in years on horizontal axis.